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Published in:
Monthly Notices of the Royal Astronomical Society

DOI:
10.1093/mnrasl/slab104

Publication date:
2021

Document version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Accurate dust temperature determination in a $z = 7.13$ galaxy

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Accepted 2021 September 3. Received 2021 September 3; in original form 2021 August 10

ABSTRACT

We report ALMA Band 9 continuum observations of the normal, dusty star-forming galaxy A1689-zD1 at $z = 7.13$, resulting in a $\sim 4.6 \sigma$ detection at 702 GHz. For the first time, these observations probe the far-infrared spectrum shortward of the emission peak of a galaxy in the Epoch of Reionization (EoR). Together with ancillary data from earlier works, we derive the dust temperature, $T_d$, and mass, $M_d$, of A1689-zD1 using both traditional modified blackbody spectral energy density fitting, and a new method that relies only on the [CII] 158 $\mu$m line and underlying continuum data. The two methods give $T_d = (42^{+13}_{-7}, 40^{+15}_{-7})$ K, and $M_d = (1.7^{+1.3}_{-0.7}, 2.0^{+1.8}_{-1.0}) \times 10^7 M_\odot$. Band 9 observations improve the accuracy of the dust temperature (mass) estimate by $\sim 50$ per cent (6 times). The derived temperatures confirm the reported increasing $T_d$-redshift trend between $z = 0$ and 8; the dust mass is consistent with a supernova origin. Although A1689-zD1 is a normal UV-selected galaxy, our results, implying that $\sim 85$ per cent of its star-formation rate is obscured, underline the non-negligible effects of dust in EoR galaxies.

Key words: dust, extinction—galaxies: evolution—galaxies: high-redshift—galaxies: individual: (A1689-zD1)—submillimetre: galaxies.

1 INTRODUCTION

Atacama Large Millimetre/submillimetre Array (ALMA) observations have revealed the presence of dust in galaxies approaching the epoch of reionization (EoR; e.g. Capak et al. 2015; Willott et al. 2015; Barisic et al. 2017; Laporte et al. 2017). This was somewhat surprising, since UV studies mapping out the cosmic star-formation rate density (SFRD) to $z \sim 10$ suggested a dearth of dust at the high-redshift end based on the blue UV slopes of low-stellar mass high-$z$ galaxies ($\beta_{UV}$; e.g. Finkelstein et al. 2015; Bouwens et al. 2016). Initially, the strong far-infrared (FIR) emission at $z > 7$ revealed by ALMA observations was attributed to the presence of unexpectedly large dust masses ($M_d$) in the observed high-$z$ galaxies, which was hard to reconcile with known dust production mechanisms that operate on that time-scale (predominantly SN and grain growth; see Leśniewska & Michałowski 2019 and references therein for the latest constraints).

This resulted in the so-called dust budget crisis, which also impacted star-formation history (SFH) estimates of high-redshift galaxies (e.g. Mawatari et al. 2020; Roberts-Borsani, Ellis & Laporte 2020). The stringent constraints on SNe dust production, coupled with the large deduced dust masses at $z > 7$, required very early stellar populations originating at $z \sim 14$ (Tamura et al. 2019). However, the conclusions on the dust masses were heavily dependent on the assumed (cold) dust temperatures ($T_d \sim 30–40$ K) for these high-$z$ sources, since in most cases only a single data point was available in the FIR continuum. Recent observations (e.g. Bakx et al. 2020) and theoretical studies (e.g. Behrens et al. 2018; Sommovigo et al. 2020) have suggested the presence of warm dust in several high-$z$ galaxies ($T_d > 60$ K), alleviating the large dust mass requirements set by their observed $L_{FIR}$ ($M_d \propto T_d^{(4+\beta_d)}$) at fixed $L_{FIR}$, where typically $1.0 < \beta_d < 3.0$). Unfortunately, the large uncertainties on derived $T_d$ at high-$z$ still hinder accurate SFH studies.

Partially due to the lack of knowledge on the dust temperature at high-$z$, the total fraction of obscured star-formation beyond $z > 4$ is also largely unknown (Novak et al. 2017; Casey et al. 2018; Bouwens et al. 2020; Gruppioni et al. 2020; Schouws et al. 2021; Talia et al. 2021; Zavala et al. 2021). This has strong implications for the cosmic SFRD; for example, some of these recent works suggest that there is no steep drop-off in SFRD at $z > 3$ (e.g. Gruppioni et al. 2020), which could indicate that we might be underestimating the contribution of highly obscured systems to the SFRD at $z > 3$ due to the bias towards UV bright objects. On top of that, most studies calculate the obscured star-formation rates and FIR luminosities of single sources either by assuming a dust temperature, and/or by $T_d \sim 60$ K. A1689-zD1, as presented here, provides a first step towards better constraining the nature of the dust budget crisis. In this Letter, we report the first dust temperature measurements at $z = 7.13$, and present the implications for the cosmic SFRD and its evolution.

The observations and the analysis are described in §2 and §3, respectively. The dust temperature estimate is discussed in §4. We present our conclusions in §5.

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between these regions in several sources at However, observations suggest the possibility of spatial separation the absorbed UV emission to be re-emitted at FIR wavelengths. that the UV and dust-emitting regions to be cospatial, relying on

\[ L_{\text{FIR}} \sim L_{\text{UV}} \times (\frac{\mu_0}{\mu_0^*})^{+1/2} \]

the intrinsic UV magnitude indicates it is a sub-

\[ M_6 \] is high, there is only little shear, and we do not account for any
differential lensing effects in this paper.

2 TARGET AND OBSERVATIONS

A1689-zD1 was identified in Bradley et al. (2008) as a bright (mAB \sim 25) z \geq 7 galaxy. Due to the foreground galaxy cluster (A1689; Struble & Rood 1999), it is magnified by \( \mu \approx 9.3 \) (Knudsen et al. 2017). Its intrinsic UV magnitude indicates it is a sub-\( L^* \) galaxy representing the bulk of galaxies at z = 7 (Ono et al. 2018). Band 6 observations at 1.3 mm by Watson et al. (2015) reported the first detection of dust beyond redshift 7, and indicated an intrinsic star-formation rate of \( \sim 12 M_\odot \text{yr}^{-1} \). Notably, the estimated dust mass of this normal galaxy (assuming 35 K) was found in tension to SFH and dust production estimates in Lesniowski & Michalowski (2019).

<table>
<thead>
<tr>
<th>Band</th>
<th>( \lambda ) [mm]</th>
<th>( F^\text{int}_{\nu} (\mu\text{Jy}) ) ( \times 10^{-14} )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>0.427</td>
<td>154 ± 37</td>
<td>This work</td>
</tr>
<tr>
<td>8</td>
<td>0.728</td>
<td>180 ± 39</td>
<td>Inoue et al. (2020)</td>
</tr>
<tr>
<td>7</td>
<td>0.873</td>
<td>143 ± 15</td>
<td>Knudsen et al. (2017)</td>
</tr>
<tr>
<td>6</td>
<td>1.33</td>
<td>60 ± 11</td>
<td>Watson et al. (2015)</td>
</tr>
</tbody>
</table>

Notes. \(^1\)Corrected for the magnification assuming \( \mu = 9.3 \) from Knudsen et al. (2017), \(^\dagger\) \( \beta_d \) is fixed to 2.03.

scaling directly from the infrared excess (IRX = \( L_{\text{IR}}/L_{\text{UV}} \)-UV relation. Both approaches suffer from the inherent uncertainty in dust temperature (since obscured SFR and IRX both scale with \( T^{4/5} \)).

Moreover, the validity of IRX-\( \beta_{\text{UV}} \) relation at high-z demands that the UV and dust-emitting regions to be cospatial, relying on the absorbed UV emission to be re-emitted at FIR wavelengths. However, observations suggest the possibility of spatial separation between these regions in several sources at \( z = 4 - 6 \) (e.g. Faisst et al. 2017) and at \( z \approx 7 - 8 \) sources (e.g. Carniani et al. 2017; Laporte et al. 2019, and Tamura et al., in preparation). In fact, this spatial separation scenario between UV and IR is also supported by theoretical studies and simulations (Behrens et al. 2018; Cochrane et al. 2019; Liang et al. 2019; Sommogvio et al. 2020). A deviating IRX-\( \beta_{\text{UV}} \) relation would impact the results of galaxies at high-z (Fudamoto et al. 2020; Le Fèvre et al. 2020) and will impact re-emission studies (e.g. MAGPHYS; da Cunha, Charlot & Elbaz 2008 and CIGALE; Boquien et al. 2019) which will be prevalent in the ALMA + JWST era.

In this letter, we use the band 9 observations to estimate the dust properties of a \( z = 7.1 \) galaxy from the spectrum directly in order to measure the obscured star-formation directly. We describe the source and data in Section 2, the fitting techniques in Section 3, and the implications in Section 4.\(^1\)

2.1 Spectral fitting

Fig. 2 shows the modified black body (equation 8 in Sommogvio et al. 2021) fitted to the continuum points reported in Table 1. We use equations (12) and (18) from da Cunha et al. (2013) to account for the heating of dust by and decreasing contrast against the CMB, respectively. We approximate the dust mass absorption coefficient (\( \kappa_d \)) as \( \kappa_d (\nu/\nu_0)^\beta_d \), with \( (\kappa_d, \nu_0) \) as (10.41 cm\(^2\)/g, 1900 GHz) from Draine (2003). We use the emcee MCMC-fitting routine, and allow \( M_d, T_d, \) and \( \beta_d \) to vary freely using flat priors, resulting in a

Figure 1. The tapered band 9 data (background and black contours; drawn at -3, -2, 2, and 3 \( \sigma \)) is shown against the band 8 continuum emission (white contours; drawn at 5, 7, and 10 \( \sigma \)). The continuum emissions appears co-spatial, and we find a 4.6\( \sigma \) dust detection in band 9.

In this letter, we combine the existing data on A1689-zD1 reported in Watson et al. (2015), Knudsen et al. (2017), and Inoue et al. (2020) with archival band 9 data from (Program ID: 2019.1.01778.S, P.I. D. Watson), see Table 1. We use the \([\text{C}] \) luminosity as reported in Knudsen et al. (in preparation), which is \( (6.1 \pm 0.7) \times 10^8 \text{L}_\odot \), and use their value for spectroscopic redshift, \( z_{\text{spec}} = 7.13 \).

For the band 9 (Baryshev et al. 2015) data, the source was observed for 95 min. in baselines ranging from 14 to 312 m. The lower and upper sidebands covered the contiguous frequency ranges of 609.4–697.6 and of 706.5–713.6 GHz. We assume a typical flux accuracy of 10 per cent. The continuum image is produced with CASA pipeline version 5.6.1-8 (McMullin et al. 2007), using natural weighting, a taper of 0.5 arcseconds, and excluding any channels within 1000 km/s of the \([\text{O}] \) line at 711.4 GHz. Fig. 1 shows the resulting image with a 0.61 by 0.67 arcsecond beam with a beam position angle of 75\( ^\circ \), with an r.m.s. level of 210 \( \mu \text{Jy beam}^{-1} \). Using CASA’s IMagit routine, we spatially integrate the emission using a 2D Gaussian profile. This results in a flux of 1.43 \pm 0.31 mJy (4.6\( \sigma \)); excluding calibration flux, with an apparent (or lensed) beam-deconvolved size of 0.81 ± 0.26 by 0.38 ± 0.22 arcsec at a position angle of 44 ± 38\( ^\circ \). The emission appears co-spatial to the UV-emission seen in Knudsen et al. (2017), although we leave further discussion of this to Knudsen et al. (in preparation).

3 METHODS

3.1 Spectral fitting

Band 9 continuum in the EoR L59

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3.2 Dust temperature from [CII] emission

We use the novel method proposed in Sommovigo et al. (2021) to derive the dust temperature in galaxies, based on the combination of 1900 GHz continuum and the overlying [CII] line emission. We provide a brief summary of this method below; for further details and verification of this method on 19 local galaxies, three galaxies at z ∼ 5 against our current best-estimates for Td and βd. To guide the eye, we include the trend of λpeak,obs with Td for βd = 1 − 2 at z = 7.1. We also overlay the wavelengths of the ALMA bands 7 through 10. We calculate this λpeak,obs using

\[
\lambda_{\text{peak,obs}} = \frac{14.42(1 + z) (T_d/K)^{-1}}{W(-a e^{-a}) + a},
\]

where \(a = 3 + \beta_d\) and \(W\) is the Lambert \(W\) function. This is the wavelength at which the continuum spectrum \(F_\nu\) peaks in frequency units (e.g. Fig. 2). This is an important distinction to keep in mind when visualising \(\lambda_{\text{obs, peak}}\) from the analogy to Wien’s law, which provides the peak of the spectrum when reported in wavelength units \(\lambda\).

Particularly for galaxies at lower redshifts and at higher temperatures, short-wavelength observations are crucial to estimate the dust temperature, whereas band 8 might be able to probe the emission peak for cold \(z > 8\) galaxies. In the foreseeable future, the high bands of ALMA (9 and 10) are the only instrument capable of probing this regime, until such missions as the Origins Space Telescope\(^4\) (Meixner et al. 2019).

\(^3\)This IR luminosity-to-SFR conversion factor, \(1.73 \times 10^{-10} M_\odot \text{ yr}^{-1}/L_\odot\), is valid for a Salpeter 1–100 M_\odot IMF, which we assume consistently throughout the paper.

\(^4\)https://asd.gsfc.nasa.gov/firs/docs/


Figure 3. Observed peak wavelength \( \lambda_{\text{peak, obs}} \) is shown against dust temperature \( T_d \) for a given dust emissivity index, \( \beta_d \). The grey shaded region shows \( \lambda_{\text{peak,obs}}(T_d) \) at redshift \( z = 7.1 \) for \( \beta_d = 2.0 - 1.0 \). We show the sources with reported dust temperatures beyond \( z > 5 \) (Laporte et al. 2019; Bakx et al. 2020; Faisst et al. 2020; Harikane et al. 2020; Sugahara et al. 2021). The shaded regions show the wavelength ranges probed by ALMA bands 7 – 10. Without band 9, we cannot probe the FIR peak on both sides and accurately estimate \( T_d \) through SED fitting, while for lower-redshift observations band 10 might even be required to accurately trace the SED.

Accurate estimates of the the dust-obscured fraction of the star-formation rate require strong constraints on the dust temperature, as \( \text{SFR}_{\text{obs}} \propto L_{\text{FIR}} \propto M_d \beta_d^{4/\beta_d} \). Our band 9 observations confirm that this relatively-cold \( (T_d \sim 40–60 \text{ K}) \) system has a very large obscured fraction of the SFR around \( \sim 85 \% \) per cent \( (\text{SFR}_{\text{obs}} = 33 \pm 9 \text{ M}_\odot \text{ yr}^{-1}) \), whereas \( \text{SFR}_{\text{UV}} = 5.7 \pm 0.3 \text{ M}_\odot \text{ yr}^{-1} \), even though it was selected to be UV-bright. The dust-obscured ratio is higher than the 61 percent found for the typically more-massive ALPINE survey selected to be UV-bright. The dust-obscured ratio is higher than the typical \( 1.5–2.0 \) \( \% \) in ‘normal’ \( \beta_d \) Main-Sequence galaxies as a function of redshift. The newest \( T_d \) estimates for A1689-zD1 are shown in red (star for SED-fit and hexagon for the \([\text{CII}]\)-based result). Dust temperatures obtained from stacked SEDs \( \text{(blue and green circles)} \) increase linearly with redshift, even though Y1’s UV-observed stellar mass is one order of magnitude lower than A1689-zD1.

The selection towards UV-bright sources might also bias towards lower fractions of obscured-to-total star-formation rate. With the discovery of so-called optically-dark galaxies (e.g. Simpson et al. 2014; Franco et al. 2018; Hatsukade et al. 2018; Wang et al. 2019; Williams et al. 2019; Yamaguchi et al. 2019; Algera et al. 2020; Romano et al. 2020; Toba et al. 2020; Umehata et al. 2020; Zhou et al. 2020; Shibuya et al. 2021; Smail et al. 2021; Talia et al. 2021), we know of the existence of galaxies without detections in optical wavelengths at high redshift. These sources, by definition, have exceedingly high obscured fractions and might well account for a substantial fraction of the SFRD at high redshift (Alcalde Pampliega et al. 2019; Gruppioni et al. 2020; Zavala et al. 2021). The typical obscured star-formation rate fraction across all \( z > 7 \) galaxies might thus be higher than predicted by UV-selected samples alone, with for example Gruppioni et al. (2020) predicting an increase in SFRD of 17 per cent at \( z = 5 \) by this population.

Recently, attempts to quantify dust obscuration at high-\( z \) have used a linear scaling between dust temperature (and \( L_{\text{dust}} \) given a fixed \( \beta_d \)) and redshift (see e.g. Schreiber et al. 2018; Bouwens et al. 2020; Vijayan et al. 2021). Other recent works have suggested that this linearly increasing \( T_d - z \) trend flattens at \( z > 4 \) (Liang et al. 2019; Faisst et al. 2020). In Fig. 4, we show the reported linear evolution of the dust temperature with redshift, adding our latest results for A1689-zD1, and where available, include the results.
from the method in Sommigovio et al. (2021). The observed dust temperature for A1689-zD1 is compatible with both a flattening (Liang et al. 2019; Faisst et al. 2020) and a linear (Schreiber et al. 2018) $T_d - z$ evolution. Meanwhile, the exceedingly-large scatter in $T_d$ at the highest redshifts (particularly at $z > 7$) prevents us from reaching a definitive conclusion on this observed evolution. Much of this scatter is due to observational limitations, and only through further short-wavelength observations of galaxies beyond $z > 7$ can we distinguish the possible scenarios. Part of the scatter could also be due to a larger source-to-source variation in $T_d$, which is for example seen by the large diversity of galaxies among the typically more-massive ALPINE sources (Le Fèvre et al. 2020). Such source-to-source variation can only be identified by larger unbiased samples looking at the dust-obscured star-formation at high redshift. Here, we note that an increased intrinsic scatter in dust temperature would significantly boost the resulting dust-obscured star-formation rate, given their strong dependence of star-formation rate on dust temperature, similar to an Eddington-type bias.

Due to the large obscured faction of the SFR in A1689-zD1, one might naively expect that this galaxy also contains an exceedingly large dust mass. Instead, the dust mass derived from SED fitting implies a dust yield of $y_d = 0.4^{+0.7}_{-0.1} \, M_\odot$ per SN. This estimate is almost an order of magnitude more accurate than the one derived without band 9 data, and most importantly, it is consistent with latest SN dust production constraints by Leśniewska & Michalowski (2019) based on the expected number of SNe given its stellar mass estimate. They find at most a $y_d = 1.1 \, M_\odot$ per SN, derived in the extreme case of no dust destruction/ejection. We note that SN yield is still highly debated, with other works suggesting that dust destruction processes might only spare 0.1 $M_\odot$ per SN (e.g. Matsuura et al. 2015, 2019; Slavin et al. 2020). In this extreme case, inter-stellar medium grain growth (Mancini et al. 2015; Michalowski 2015) or more exotic dust production mechanisms might well be required at $z > 7$, such as dust produced in supershells (e.g. Martínez-González, Silich & Tenorio-Tagle 2021) or in the wake of Wolf-Rayet stars (e.g. Lau et al. 2021).

ACKNOWLEDGEMENTS

We would like to thank the anonymous referee for their insightful comments and suggested additions. This paper makes use of the following ALMA data: ADS/JAO. ALMA 2011.1.00319.S, 2012.1.00216.S, 2013.1.01064.S, 2016.1.00954.S, and 2019.1.01778.S. TJL CB and YT acknowledge funding from the ERC Advanced Grant INTERSTELLAR H2020/740120 (PI: Ferrara). The Cosmic Dawn Center is funded by the Danish National Research Foundation under grant number 140. This project has received funding from the European Union’s Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement number 847523 ‘INTERCTIONS’. DW and SF are supported by Independent Research Fund Denmark grant DFF–7014-00017. Any dissemination of results must indicate that it reflects only the author’s view and that the Commission is not responsible for any use that may be made of the information it contains.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.
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